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Measurement of Solar Radius Changes

Abstract. *Photoelectric solar radius measurements since 1974 at Mount Wilson show no change in the solar radius, with a limit of about 0.1 arc second (1 standard deviation), over the interval. The limit is set by residual systematic effects.*

Several studies of possible secular and periodic variations of the solar radius have yielded conflicting results (*1–7*). The data analyzed have been almost entirely historic measures from meridian circles, heliometers, transits of Mercury, and eclipse timings. All of these data are based on visual estimates. None of the daily measurement programs are currently obtaining data. We present here results of daily photometric measurements of the solar radius over the past 7 years at the Mount Wilson Observatory.

Measurement technique. One part of the reduction of the Mount Wilson daily full-disk magnetograms is a determination of the radius of the solar image. Although high precision is not required for the magnetic analysis, the formal error of the daily values is about 0.1 arc second. These data have been taken for a number of years, and we have examined them for a secular variation in the solar radius. Our measurements are not absolute, as the focal length of the telescope is not known to sufficient precision; a nominal radius of 960.0 arc seconds is used to convert our scale to arc seconds.

The Mount Wilson 150-foot Solar Tower Telescope and magnetograph have been described in detail by Howard (*8–10*). The daily observation is a boustrophedonic scan of the full disk in the wings of the 5250.2-Å FeI line. The objective, polarizing optics, and spectrograph aperture (12.5–arc second square) are fixed. Scanning is done by moving the guider sensors located at the prime focus image; the guider error signals drive the second flat mirror, moving the solar image across the aperture. The (x, y) position of the guider sensors is recorded with each data sample. One x, y encoder unit corresponds to 0.28 arc second. Scan lines are aligned perpendicular to the solar pole. The observation is started in the solar north or south by random selection. Each scan line extends off the disk and onto the sky at both ends. There are about 150 scan lines in each observation.

The average intensity of the disk is computed from the data, and a linear trend of intensity as a function of time is removed from the data. This linear trend averages $\lesssim 4$ percent, so systematic nonlinearity of our photometric scale may be ignored. The limb is defined as the steepest point in the limb darkening curve; at the wavelength used, this corresponds to a contour level of measured intensity of 0.25 of the disk average intensity.

The (x, y) positions of the limbs in each scan line are found by linear interpolation of the intensities. The equation $R = [(x - X_0)^2 + (y - Y_0)^2]^{1/2}$ is then solved by a least-squares method for the center of the image (X_0, Y_0) and the radius R. Separate solutions are obtained for the eastward and westward scan lines to allow for backlash in the drive mechanisms. The radius measure R_0 is the average of these two solutions. The radius solutions are done iteratively, with points far from the derived limb excluded. This rejects data where the limb is obscured by the guider sensors or a passing cloud. Typically, 20 points out of 150 are so rejected. The formal probable error of the least-squares solutions is typically 0.06 arc second, with little variation about that value. Some observations are taken under poor photometric conditions, with variable sky transparency or scattering. On these days the formal probable error is much larger than normal, ≥ 0.12 arc second. We rejected 133 days on this basis. No bias is introduced into the data set by this criterion because the formal probable error is uncorrelated with the raw radius measures or the radius residuals, and the actual errors are much larger than the formal errors and set by effects other than the internal photometric consistency of an observation.

Once the limb position is found, the scattered light of the optics plus atmosphere is determined. Scattered light is defined as the average intensity measured at a distance ($2.8 + A/\sqrt{2}$ arc seconds) outside the limb, where A is the aperture size; this guarantees that all parts of the aperture, including the corners, are off the limb, with an arbitrary 2.8–arc second allowance for seeing ripple and mechanical jitter.

Figure 1 shows the raw radius measures as a function of time. In the interval 26 July 1974 to 1 April 1981 there are 1412 measurements.

Reduction procedure. Sources of variation in the measured image size, aside

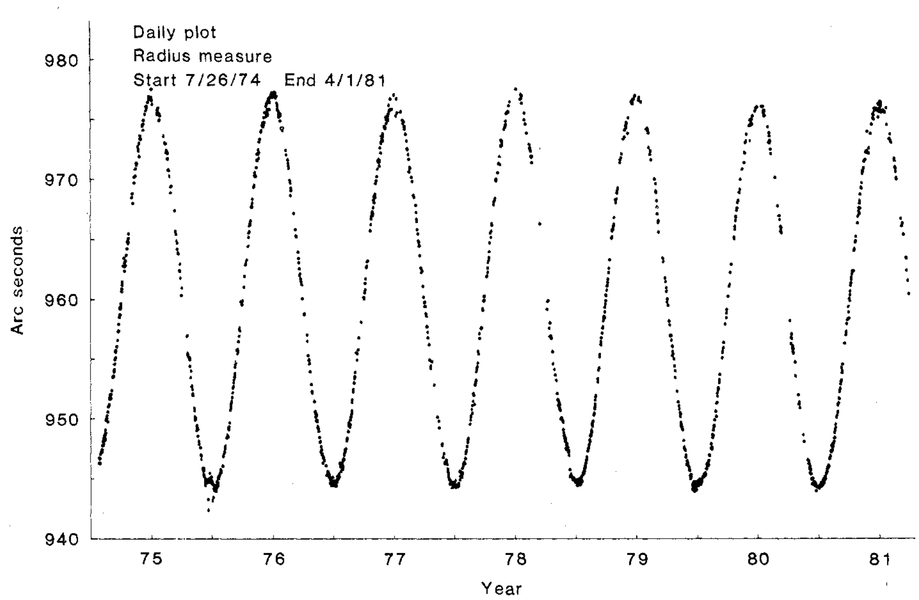

Fig. 1. Solar radius observed with the Mount Wilson magnetograph. The arc second scale is not absolute; a mean radius of 960.0 arc seconds is assumed. There are 1412 observations in this interval.

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from any true solar radius changes, are the observer-sun distance and the sources summarized in Table 1. We correct for the observer-sun distance by including terms for the earth's orbit and rotation and the moon's orbit (*11*).

Differential refraction in the earth's atmosphere decreases the solar diameter that appears vertical to the observer, but does not alter the horizontal diameter. The radius of a circle that is fit to this flattened image is thus decreased. To remove this effect, each day's raw radius measure is increased by half the average of the differential refractions at the start, middle, and end of the observation. The formula used is derived from Smart (*12*) with proper correction for atmospheric temperature and pressure at the time of the observation. Because the average amplitude of the correction is only 1/4 arc second, any second-order error that would require point-by-point correction of the original data was deemed unimportant.

Defining the limb as an isointensity contour requires that sky brightness off the disk be constant. This is not always true if there is scattered light in the atmosphere or optics. For scattered light intensities of a few percent of the disk center intensity, and for $A << R_0$, we consider the situation when the aperture is partially off the limb and find that scattered light increases the apparent solar radius by the amount $\Delta R_0 = I_s/I_d \times A$, where I_s and I_d are the intensity of the scattered light just outside and that of the disk just inside the limb. The principal source of scattered light in the data used here is dirt on the optics; 65 additional days with poor photometric conditions were rejected because of scattered light in excess of 0.5 percent of the disk center brightness above the level of contemporary observations.

Table 1. Factors affecting the measured radius.

Cause	Maximum and minimum changes (arc seconds)
Earth's atmosphere	
Differential refraction	−0.13 to −0.75
Instrument	
Scattered light	0.08 to 2.2
Aperture change	0.00 to 0.05
Prism/Polaroid	0.00 to −0.06
Temperature	± 0.16

The spectrograph aperture size was changed during the interval used (*9*). There is a small aperture correction to the radius measure caused by the nonlinearity of the limb darkening and our definition of the limb as a constant isointensity contour. This correction amounts to $\Delta R_0 = 0.17\Delta A$, determined empirically from the radius residuals.

For an interval of about 26 months (May 1976 to July 1978), a sheet of Polaroid material was used to provide the linear polarizing element in the magnetograph analyzing optics. For the rest of the period, a Glan-Thompson prism was employed instead. The difference in optical path length between these elements is not small, and a separate fit to the residuals for this interval indicated a change in radius of −0.06 arc second. This correction was applied to the residuals for this interval.

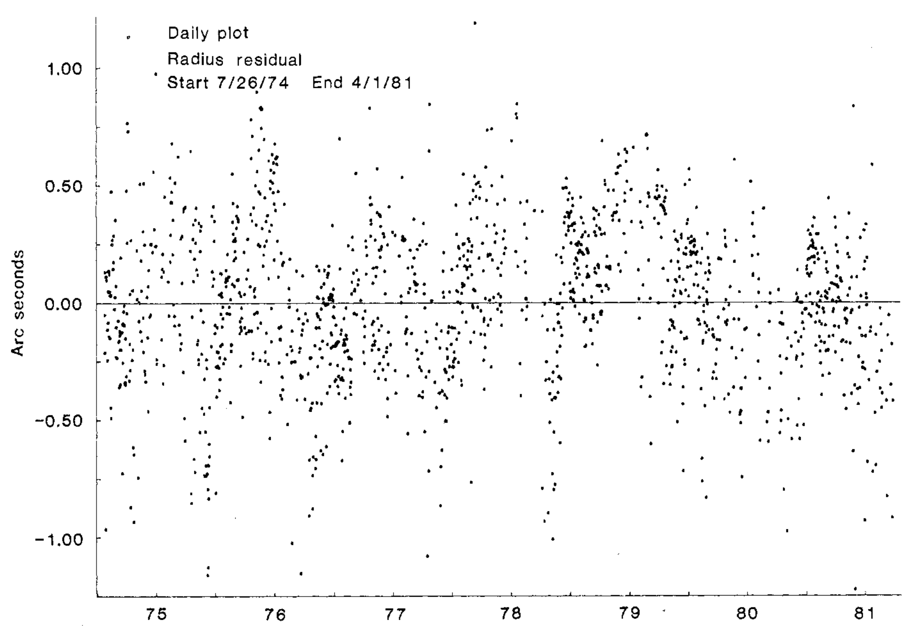

Fig. 2. Variations in the solar radius observed with the Mount Wilson magnetograph. All known effects have been removed from the data in Fig. 1 to produce the residual values plotted.

The telescope is a simple unfolded refractor with a focal length of 46 m. For a temperature variation of 1°C one might expect a change in the measured radius of about 0.012 arc second, corresponding to an expansion of the steel tower by 0.6 mm. The thermal expansion of the steel screws used to position the image equals this effect but may add to or subtract from it, depending on whether the entrance aperture is inside or outside the true focus of the lens. Each day the temperature in the (unheated) observing room was recorded. A least-squares fit for a linear relation of the radius residuals to the temperature gives a temperature effect of the predicted value in the direction predicted by the effect of the linear polarizer discussed above, that is, the radius decreases as the temperature increases; our aperture is slightly inside the true focus. The empirically determined temperature effect was used to correct the radius residuals. There is no significant secular trend of the measured temperatures which might remove or enhance long-term radius variations.

There are other effects that, in principle, can affect the measured solar radius. Many are listed here; none has a significant effect on the radius.

A change in telescope focus will make a large change in the measured radius. During the interval covered by this study no changes were made in the focus setting.

Because the scan lines across the solar disk are perpendicular to the solar meridian, we expect that the radius in the east-west direction is better determined than that in the north-south direction; there are more points in the limb solution near the equator than near the poles. The angle made by the sun's pole with the vertical direction in the sky varies with time of day and season, and one might expect this to introduce a slight systematic variation of the measured radius; examination of the residuals as a function of this angle shows that this effect is too small to be seen.

Variations in the optical path length due to changes in filters and analyzing crystals, or to changes of barometric pressure, are negligibly small.

That we do not see the true solar radius because of projection effects—we are not an infinite distance from the sun and therefore cannot see quite half the solar surface—leads to overestimation of the radius by about 0.01 arc second. The annual variation of this effect may be ignored.

It is not impossible that the tower

structure is slowly settling, thus changing the image size. If we exclude the possibility that the settling began when our radius measures started, we can set some limits on the magnitude of this effect. The 150-foot Tower Telescope is actually two towers (*13*); one holds the optics and the other, on completely separate piers, holds the dome. Over the 70-year life of the tower, a differential settling of as much as 20 mm would easily have been noticed. This is 0.3 mm per year, which would result in a change of only 0.006 arc second per year, or 0.6 arc second per century, as an upper limit.

Solar magnetic regions at the limb should affect the measured radius because the intensity near the limb is changed by the presence of dark sunspots or bright faculae. Based on our observations of magnetic regions near the limb, this effect is $\lesssim 0.01$ arc second and can be disregarded for this study.

Results. Figure 2 shows the radius residuals obtained after correcting the raw radius measures for the effects listed in Table 1. The standard deviation of a single residual is about 1/4 arc second. The residuals do not have a Gaussian distribution; the dominant error is not random, but systematic. Two problems are apparent: (i) residuals tend to clump for periods of about 40 days (determined by autocorrelation), with larger variation between clumps than within a single clump, and (ii) there is an annual pattern, dominated by episodes of large negative residuals in the spring. Because the systematic variations of the residuals have abrupt onsets and the largest variations repeat annually, we are convinced these systematic errors originate in the instrument or observing procedure, but have been unable to identify the specific causes.

In a 40-day interval we have about 25 observations. The formal error of any parameter measured from the residuals should thus be increased by $\sqrt{25}$ because we do not have independent samples. Including this factor, we fit the residuals separately for a secular trend and an 11-year sinusoid. The results were a trend of 0.2 ± 1.6 arc second per century, or a sinusoid of 0.1 ± 0.1 arc second (errors are $\pm$ 1 standard deviation). Both results are consistent with zero radius variation over the past 7 years.

Discussion. It is unfortunate that the systematic effects remaining in our data are so large. The limits on radius variations that we are able to set are not improvements over previous results (*3*, *5*, *7*) and thus do not resolve discrepancies among those results. The program of observations at Mount Wilson is continuing, and we may be able to find and eliminate the sources of systematic error. The random errors of measurement appear to be about 1/5 or 1/6 arc second per observation; a data set of several years duration with errors of that magnitude would be a significant improvement over previous radius measurements.

When one considers that the instrument, the observing procedure, and the standard radius reduction were not optimized for this purpose, the size of our residual errors is encouraging. A ground-based instrument designed for this specific observation should be capable of extremely high precision.

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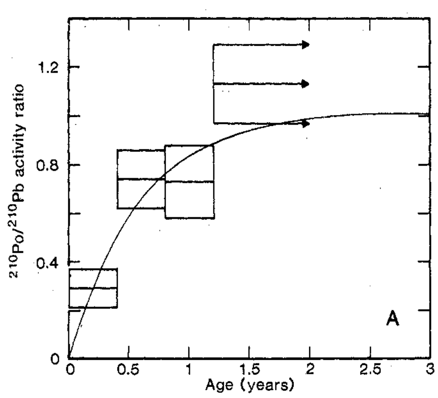
Growth Rate of a Vesicomyid Clam from the Galápagos Spreading Center

Abstract. *The shell of a 19-centimeter-long vesicomyid clam, collected live at the Galápagos spreading center hydrothermal field, was sampled along growth lines and analyzed for members of the* ^{238}U *and* ^{232}Th *decay series. The growth rate, determined from the* $^{210}Po/^{210}Pb$ *and* $^{228}Th/^{228}Ra$ *couples, is about 4 centimeters per year along the axis of maximum growth, which is 12 centimeters long. This yields an age of 3 to 4 years for this clam.*

After the discovery of large white clams associated with the Galápagos spreading center by Lonsdale (*1*), a series of exploratory dives were made at the site by the submersible *Alvin*. The shell of a dead vesicomyid clam, collected during the first series of dives in February and March 1977 (*2*) from the site designated Clambake I, was sent to us, and we made a preliminary estimation of the growth rate on the basis of a whole shell analysis for the natural radionuclides (*3*). We first set upper limits of age and then used the $^{228}Th/^{228}Ra$ activi-



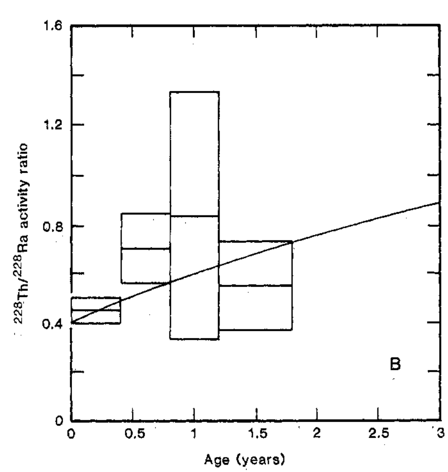


Fig. 1. (A) The $^{210}Po/^{210}Pb$ activity ratio growth curve with an initial value of ^{210}Po equal to 0. The sample ratios were positioned along the curve by eye to obtain the age of the clam; continuous deposition is assumed. The last sample is in equilibrium and therefore could be about 2 years old or older. Its age is constrained by the $^{228}Th/^{228}Ra$ data. (B) The $^{228}Th/^{228}Ra$ activity ratio plotted as a function of age (determined from the $^{210}Po/^{210}Pb$ data) for sequential layers in the clam shell. The best fit curve for $^{228}Th/^{228}Ra$ growth with time requires an initial $^{228}Th/^{228}Ra$ activity ratio of 0.4. The oldest sample is less than 2 years old.

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